Morphological, electronic, and chemical structure of lattice-mismatched III-V heterojunctions – FY02 Nuggets

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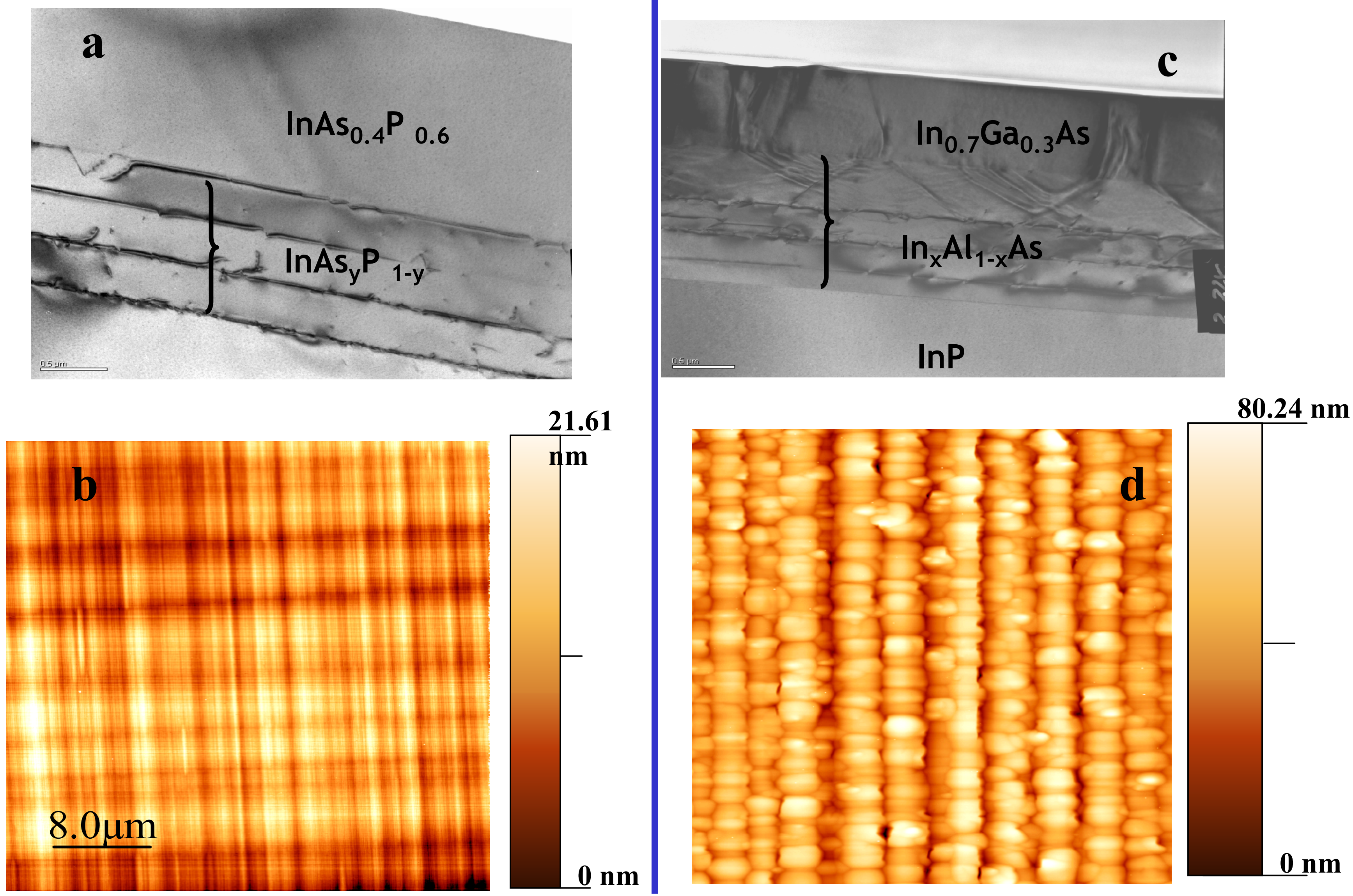
Overall Summary. There is a great need to develop a range of substrate lattice constants that can support advanced and future device technologies that can exploit the wide range of properties presented by semiconductor materials. For semiconductors with bandgaps in the infrared region of the electromagnetic spectrum that are important for communication systems via the development of both optical device and high speed electronics, the primary substrate available is InP. Methods to alter the InP surface lattice constant to achieve "virtual" lattice matching for growth of a wider range of mismatched III-V overlayers are needed since direct growth of these materials onto InP results in device-killing defects. The purpose of this FRG program is to investigate strategies to achieve device-quality "virtual substrates" where the final surface lattice constant can be tailored to support such device technologies. The primary scientific investigation centers on the growth, properties and applications of III-V compound graded buffer layers where the lattice constant is engineered with either the group III elements (cation sublattice) or the group V elements (anion sublattice). The materials of primary focus are InAsP, InAlAs and InGaAs, all grown on InP substrates by molecular beam epitaxy. Both buffer layers and heterostructure overlayers consisting of several strategic combinations of these materials are being evaluated. The growth fundamentals and their relation to bulk and atomic-scale material properties will be established via coordinated efforts in growth, structural and electrical characterization, interface and chemical characterization, surface characterization and theoretical support on the formation and properties of specific interfaces.

For this year, this report contains several nuggets that demonstrate extremely promising properties of relaxed InAsP alloys as graded buffers on InP to achieve device quality virtual substrates based on InP with variable lattice constants, as opposed to more conventional cation-based grades such as InAlAs and InGaAs.

$InAs_{0.4}P_{0.6}$/$InAs_xP_{1-x}$/InP | **$In_{0.70}Al_{0.30}As$/$In_xAl_{1-x}As$/InP**



RMS roughness: 3.2 nm

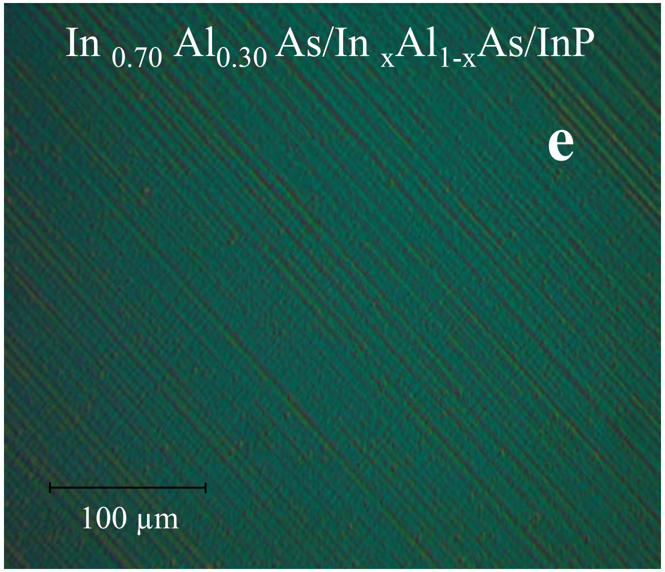
RMS roughness: 8.8 nm

This page shows a comparison of anion (group V) and cation (group III) relaxed buffer layers using InAsP and InAlAs, respectively, grown on InP substrates. The total lattice mismatch for both cases is 1.2%, to provide unambiguous comparison. Triple axis x-ray diffraction measurements confirmed that the final layers are nearly totally relaxed (>97%) for each case. However, significant differences in the nature of the relaxation was evident,with substantial lattice tilt (~ 500 arcsec) within several layers of the cation (InAlAs) graded structure and in contrast, negligible tile (20 arcsec) for the anion (InAsP) grade.

The figures show the dramatically different structural features between these two systems (left/right). For InAsP no threading dislocations are detected by cross sectional TEM in the cap layer in figure a, indicating that the thread density must be less than 10^7 cm^{-2}. Etch pit density (EPD) and Electron Beam Induced Current (EBIC) measurements made show an average EPD and dark spot density of ~ 1-3x10^5 cm^{-2} for the relaxed cap layer. Plan view TEM is currently being performed to verify the density of threading dislocations. AFM results in figure b reveals extremely ordered, uniform and shallow surface crosshatch for InAsP grades. Coupled with the low defect density using InAsP, this indicates that very efficient relaxation via misfit dislocation nucleation and motion has occurred.

The InAlAs (cation) graded structure is quite different for the same amount of lattice mismatch. The TEM crosss section shown in figure c indicates substantial defect structure penetrating the relaxed cap layer (note that InGaAs lattice matched to the top step of the InAlAs graded buffer was used here, but results are identical for thick InAlAs caps), with surface roughness evident even at the scale of TEM cross sectional imaging. The AFM scan in figure d indicates the much rougher surface for the InAlAs grades, noting the factor of ~ 3 increase in RMS roughness compared to the InAsP based counterpart as shown in the figure. In fact, to observe the crosshatch in graded InAlAs, we had to go to a larger viewing scale using Nomarski imaging – next slide.

Lower resolution phase contrast microscopy surface images showing crosshatch patterns in both mismatched systems.



This page shows low magnification Nomarski images of the two structures shown in the previous slide. The crosshatch pattern that is expected for relaxation via graded buffers is now clear for the InAlAs graded structure, figure e. It is also present but very faint for the InAsP graded structure, figure f, at this scale. The smoother surface of the latter is again clear.

Explanation and significance of results

- Extremely low defect densities have been demonstrated for relaxed InAsP graded buffers grown on InP substrates. Films exhibited very low surface roughness, with near complete relaxation of the 1.2% misfit confirmed by triple axis XRD. With this high structural quality in spite of the lattice mismatch, InAsP relaxed graded buffers should be a very viable approach to achieve so-called “metamorphic” buffers to support a wide range of electronic and optical devices within the infrared bandgap region. Preliminary devices being generated on another program are showing outstanding early results, supporting the evidence of extraordinary material quality for this mismatched system`.

- Comparable cation based grades using InAlAs were also shown to be effective in relaxing the same misfit strain sufficiently, but with the cost of a much higher defect density ($\sim 10^7$ cm^{-2})and greatly increased surface roughness that make it inferior for device applications.

-The low defect density and highly uniform crosshatch with minimal roughness for the InAsP graded layers are attributed to advantages of engineering the lattice constant and composition exclusively on the anion sublattice, independent from the cation species which dictates growth rate. This decoupling significantly lessens the constraint on the growth parameter space needed when growing lattice mismatched structures in III-V systems as compared to, e.g., InAlAs, where the group III species dictate both growth rate and lattice constant change (composition), which restrict the ability to control and optimize the rate of strain introduction for efficient relaxation. Moreover, the relaxation being achieved with this dislocation density implies high dislocation glide velocities for the InAsP relaxed alloy system. This fundamental aspect is currently under investigation.

Dissemination of Results

-Three manuscripts are either submitted or near completion at the time of this writing, for various journals.